

## **TEST EFFECTIVENESS TREND OBSERVATION**

### **Relationship of Test Program History to Flight History (Voyager and Magellan Radio Frequency Subsystem)**

#### **REFERENCE:**

Brown, A.F., "Development of a Method for Flight Anomaly Characterization," JPL D-11382, (RISR 16302-2), January, 1994.

#### **CONCLUSION:**

A correlation of in-flight problem/failures (P/Fs) on the Voyager and Magellan radio frequency subsystem (RFS) with ground -test P/Fs revealed that the test effectiveness of the environmental test program was compromised by other product assurance functions such as parts selection and screening, circuit design analysis, failure modes and effects identification, and lack of requalification of both inherited hardware and hardware reworked after a test failure.

#### **DISCUSSION:**

The objective of this study is to determine where the environmental test program may not have been effective in screening problems that occur later in flight, and conversely where it is effective in such screening. The approach involved comparing in-flight problems or failures (P/Fs) having specific characteristics identified in the Reference with ground-test P/Fs screened for similar characteristics. These characteristics included hardware type, failure cause, environmental stresses, and failure modes.

Seven in-flight problem/failures (P/Fs), cited in the Reference as having a major or potential major impact on the flight mission were investigated. The in-flight P/Fs occurred on Voyager and Magellan.

Four in-flight Voyager PFRs that had a major impact on the mission, or potential for a major impact, occurred within the first 7.5 months of launch. Another major anomaly on the RFS occurred after 15 years and could be attributed to aging.

Two anomalies that occurred, one on each S/C, were caused by a combination of factors. They caused significant degradation in the RF power output of the solid state amplifier (SSA) in the high power mode (with some degradation in the low power mode on Voyager 2). The cause was time vs temperature degradation of the power amplifier transistor (MSC 3005) resulting from migration of the aluminum contact material, exacerbated by a poor heat sink solder joint. Although a life -limiting mechanism, the

migration itself occurred earlier than expected. The S-band TWT life was conserved by switching to low-power-mode operation on the SSA.

Another significant RFS failure occurred when uplink lock could not be established on receiver 2 on Voyager 2 due to the failure of a tracking loop capacitor. This capacitor was a Dearborn PT 40452-031. Encounter activities were compromised by this failure.

The other significant RFS failure, receiver 1 on Voyager 2, occurred after it was switched on following the problem with receiver 2 note above. The most probable failure cause was a short within the receiver power converter due to a conductive particle between the supply line and the chassis.

In order to understand the problem with the MSC 3005 transistors, an extended life test at 1015°C above the measured in-flight temperatures was performed on two complete residual SSAs and four RF transistors of the type in the SSA. Additional transistors were added later. It is believed that the rate of degradation on a good device is proportional to the junction temperature.

A transistor exhibiting a high thermal delta (~20°C) and its heat sink and solder joint were carefully removed from the chassis and metallographic and SEM pictures prepared for examination. Such a thermal delta led to an in-flight junction temperature of about 120°C. The examination did not show any incompatibilities of materials or fundamental problems as an integrated system. It was concluded that the high thermal delta was caused by cohesive separation of the solder, both underneath and around the periphery of the part. The reason for this was attributed to either improper controlling of the soldering temperature/time relation, or that the part was moved slightly during the time the solder was solidifying.

It was believed that a 120°C junction temperature was not sufficient to cause the degradation observed on transistors under test, on a normal transistor of this type. Therefore, some of the test transistors were sent to the manufacturer, Microwave Semiconductor Corp., for analysis. A destructive physical analysis performed revealed that the aluminum emitter fingers were dissolving into the silicon base material. Although this is a normal wear out mechanism for this type of transistor, it occurred too early in the life of the transistor. The analysis did not reveal the reason for the early occurrence of the wear out. It did show that the amount of RF degradation is proportional to the degree which the emitter fingers dissolve into the base. One potential cause of the transistor problem was the screening technique used for power transistors that may have over-stressed the parts. The screening conditions were later changed after the Voyager program.

For whatever reason some of the transistors exhibited the early wear out phenomena, it was accelerated by the poor solder-joint thermal conduction since the wear-out mechanism is proportional to time and temperature. Therefore, the problem had two interlocked causes. First, the existence of transistors in a purchased lot that exhibit a faster-than-normal wear-out mechanism combined with poor solder-joint heat sinking that accelerated the mechanism. Any weeding out of such defective transistors is usually done by an extensive burn-in, not environmental testing per se. The prevention

of the poor heat sinking depends on the proper control of the soldering process and on detection of inadequate solder joints. Since usual visual inspections are not adequate, stress-related environmental testing, such as powered -on vibration, or a power-on thermal scan would be effective. In the latter, the transistors with bad solder

joints would show as "hot spots". Although, powered -on vibration was performed on the Voyager RFS, the problem may not have been uncovered due to the type of instrumentation used and whether it could detect changes in electrical conductivity at the solder joint commensurate with poor thermal conductivity.

The third significant in-flight Voyager RFS failure, where encounter activities were compromised, occurred when the uplink lock could not be established on Voyager 2 receiver 2 due to a tracking loop capacitor failure.

The capacitor, a PT 40452 -031 manufactured by Dearborn, failed during ambient fabrication/assembly testing of the Voyager proof test module (PTM), and again during ambient testing of the PTM at the Kennedy Space Center. The first failure resulted in a replaced capacitor which had shorted. The capacitor was removed and taken apart. Dielectric punctures were observed and considered typical of the self healing characteristics of this type of construction. These type of defects can be cleared with the application of voltage across the capacitor, and the condition of the capacitor was not considered abnormal or a reason for failure.

The holes in the capacitor, known as electrical clearing sites caused by small defects in the 2 micron thick polycarbonate dielectric, are normally cleared during screening electrical tests by applying 75 V prior to final acceptance of the capacitors. The process of performing electrical measurements, while thermal cycling, could clear defects in the capacitor making it difficult to detect shorts.

The second failure in a PTM capacitor of this type occurred after the launch of Voyager 2 and prior to the launch of Voyager 1. Analysis of the second failed capacitor led to the conclusion that the most probable cause for these failures was small particles cold flowing through the polycarbonate causing a short from plate to plate. The manufacturer of the 2 micron polycarbonate metallized foil did not filter particular contaminants less than 7 micron. This led to the possibility that entrapped conductive contaminants not screened by the 75 V defect clearing voltage, could with time, flow through the polycarbonate to form an electrical short under the low voltage application to which the transistor was applied.

At this point it was assumed that other capacitors from the same lot as both the failed ones had similar problems. Although the second capacitor failed prior to the launch of Voyager 1, and had undergone extensive analysis, it was decided not to retrofit the Voyager 1 RFS (the Voyager 2 RFS suffered this type of flight failure) with a capacitor from a different lot because: (1) of significant slip in launch schedule; (2) of a requirement for blind mating of coax connections to the transponder resulting in added risk; (3) the replacement capacitors had only 168 hours of screening compared to 1500 hours on the ones already in the transponder-leading to a trade-off between known risk

assumed by using capacitors from a lot with significantly more screening time and capacitors with unknown risk from a different lot with less time.

At the time of the second failure of the tracking loop capacitor, it was recommended that a study of the polycarbonate film be accomplished to verify the assumptions made about the film, to determine optimum clearing voltages, optimum screening techniques, and rate of resistance clearance.

Future use of this generic type of capacitor for low voltage and high impedance applications, as was the case here, was recommended against due to the requirement for a higher clearing voltage. This requirement is due to the nature of its construction and materials. Unfortunately for Voyager 2, the implications of the use of the PT 40452-031 and its limitations were not understood prior to launch. Therefore, the parts screening program and the hardware environmental test program, did not provide the information to make a determination of the existence of the problem, in spite of one actual failure on the PTM prior to the Voyager 2 launch. The first failure report of this capacitor was closed out on the assumption that it was a lot problem instead of a generic problem.

The fourth in-flight failure on one of the Voyager S/C occurred on Voyager 2 when a short to the chassis within the receiver completed a short circuit across the 30 V supply when combined with a short to the chassis of the 30 V return that had occurred earlier on after launch. The second short caused the fuses in the power converter to open. A very detailed ground based analysis led to the conclusion of the conductive particle shorting the power converter to the chassis in the presence of the first short.

In-flight tests with the S/C were also performed to confirm the existence of the short to the chassis of the 30 V return. A 30 V return short creates a number of single points where failures such as the receiver failure can occur. The existence of the first short was not absolutely demonstrated. Either short by itself was not detectable by normal means. The actual mechanism causing the short resulted from a workmanship problem-using a screw that was too long, or tightening down too hard, breaking an end cap and causing metallic particles to fall into the chassis. The electronics was coated with a conformal insulating coating which was not applied uniformly over sharp edges and other areas, leading to exposed areas susceptible to shorting.

The final report on the study recommended that circuit analyses be performed to identify potential short-circuit connections leading to failures such as this one. Actually, the failure could be attributed to a combination of poor workmanship, packaging, failure to recognize potential multiple short-circuit paths, and failure to recognize the complex failure mode that ensued. Although environmental testing can play a role in identifying potential faults, inspections of the physical layout of electrical connections that lead to a more fault tolerant design probably will be more important in preventing such future problems.

The three significant in-flight Magellan RFS PFRs occurred between 4.6 months and 32 months after launch.

The first PFR consisted of a total of 5 TWTA shutoffs that were mitigated by operational workarounds. Fortunately, they occurred during cruise and not during a critical time such as Venus orbit insertion (VOI). There were four such TWTA incidents before launch during ground testing. No long-term corrective action was recommended.

The second PFR occurred at 22.5 months resulting in significant degradation to transponder B due to the presence of a sweeper spur caused by a failure in the last stage of the X-band downlink exciter; capability was down to 43%. The failure seriously degraded the transmission capability by preventing the subcarriers from operating. Transmission was switched to transponder A at this point, and therefore, the only consequence was a significant loss of redundancy.

Although the cause of the failure was unknown, the most likely cause was a damaged chip capacitor, a CDR01 type, in the last stage driver circuit. It was postulated that value of the capacitance changed due to sensitivity to thermal stresses; such capacitors often crack when over-stressed thermally. The thermal stress involved here was a large number of thermal cycles after the stress of interplanetary vacuum. Prior to launch, the capacitor underwent a number of soldering operations leading to the possibility of damage during the assembly and alignment of the module. Had the capacitor not have been damaged prior to launch, it might have survived the flight environment.

The reason for the rework was a warning from the radio manufacturer that some of the internal ground straps did not have sufficient stress relief and had a high probability of breaking. Upon disassembly, broken straps which would have led to potential flight failures, were found.

There was one test PFR, that occurred on the S-Band resulting in low power output in which all chip capacitors were replaced. No further detail is provided, so that this occurrence could not be used to shed any further light on the chip capacitor that failed in flight.

The third Magellan RFS PFR occurred 2.7 years after launch when the subcarriers on transponder A were lost. The S/C was switched over to transponder B which had only 43% capability. At this point the primary objectives had already been met; further RADAR mapping was precluded but the gravity science measurements could be accommodated.

The failure was attributed to leaky glass passivation on an op amp that allowed trapped moisture to form an acidic compound that found its way to a resistor, etching it and causing it to fail. Although the passivation system was suspect and a failure occurred in ground testing, schedule problems and the lack of significant data on a new passivation process at the time restricted the use of devices with the new system. Also, rigorous testing of the older devices in the same lot in water produced no failures. Devices with the older passivation system are no longer used.

## **SUMMARY:**

None of the flight failures discussed here appeared to depend solely on some inadequacy of the environmental test program. Parts selection and screening were important, as well as, circuit design analysis and failure modes and effects identification were important with regard to the Voyager failures. A cold solder joint that played a significant part in accelerating one failure mode might have been found through powered-on testing, either dynamic or thermal.

A generic type of failure in another electrical part should have been found through better screening and comparison of parts properties with design criteria -i.e. this was a design practices issue. The fourth failure might have been prevented by a more intensive circuit analysis to detect potential shorting paths. Environmental testing might have helped in isolating potential shorts to the chassis if they had existed--although it appeared that both shorts occurred after launch.

The RFS anomalies that occurred on Voyager had a potential for a very serious impact on the mission. It was only the use of work -arounds and redundancy that saved the mission. The key issue of how the test could have been more effective can be discussed both from the viewpoint of what may have been missed, and other potential problems that were caught before launch.

A scan of the list of Voyager PFRs associated with environmental testing on the Voyager RFS, including ambient testing, indicates that 143 had a failure effect rating greater than or equal to 2. Although there were numerous TWTA failures among these tests, none were recorded in flight. Therefore, the test program seems to have been effective in preventing in-flight TWTA failures, since there were none.

Three of the four major RFS flight failures were parts -related problems. The environmental test program was effective in detecting a number of parts failures including two on one of the types of parts that failed in flight. A number of workmanship/fabrication problems were uncovered; one of the flight failures involved this type of problem. One of the test PFRs involved a metal -flake short, one of the problems occurring in flight. There were also several defective potting problems, such problems were probably contributory to this flight problem.

Therefore, the test program was effective in uncovering the types of problems that caused significant failures in flight on the Voyager RFS. In one case the test problem was not successfully diagnosed until it had occurred a second time on the PTM, after the S/C on which the flight failure occurred, was launched. In another case, it appears the parts screening and selection process was at fault, for the most part. The detection of the part defect required a life test instead of an environmental test (or ambient). Although, it appears that the thermal heat-sinking problem might have been of the type that could be found normally during powered -on testing, lack of proper instrumentation may have prevented detection.

The other problem that occurred in flight, the short to the chassis would have been difficult to detect during testing. It required the simultaneous occurrence of two shorts

to the chassis; and prior identification of the potential problem would have required failure modes effects analysis to identify the failure paths.

The TWTAs on Magellan were inherited from the GSFC TIROS/NOAA and Air Force DMSP meteorological satellite programs and were not required to have a qualification test. The fact that TWTA shut offs occurred in the flight acceptance tests indicates that an inherited design characteristic may have been at fault. This would point to the necessity of a detailed review of inherited designs and possible requalification of inherited hardware for different uses than originally intended.

The issue of test and flight P/Fs on TWTAs was to be the subject of a Test Effectiveness Trend Report on TWTAs because they been troublesome in the past on other flight programs. This effort resulted in a terminated trend investigation report (an aborted test effectiveness trend analysis report). It was concluded that TWTA design is so specific to each flight program that generic recommendations for future projects would be difficult to make in view of the unique design and test characteristics required for each case. It was also felt that solid state amplifiers are the technology of the future, and therefore lessons learned on TWTA testing would soon become obsolete.

The degradation of Magellan transponder B was attributed to a faulty chip capacitor that may have been damaged during soldering operations involved with rework. It appears that there should have been a better plan for qualification of components after a significant amount of rework, although the P/F database does not provide enough information on the chip capacitors to verify this.

The last RFS failure occurred after the primary mission objectives had been met. It is also difficult to relate this failure to the test program because the device most likely responsible for the failure was rigorously tested for the failure mode implicated. The Project was also prevented from selecting devices with a newer technology due to schedule constraints.

Regarding Magellan, it appears that the lack of test effectiveness here was due to failure to requalify inherited hardware. Also implicated is the failure to requalify hardware after significant rework due to prior Magellan test failures.